Chewing simulation of zirconia implant supported restorations

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Abstract: PURPOSE To test three potential prosthetic material options for zirconia implants in regard to their mechanical properties, loading and retention capacity as well as to record abrasion after chewing simulation followed by thermocyclic aging. METHODS Molar crowns (n = 96) of three different computer-aided design/computer-aided manufacturing (CAD/CAM) materials were produced and cemented on zirconia implants (ceramic.implant, Vita) with a diameter of 4.5 mm. Monolithic zirconia (Vita YZ [YZ] with RelyX Unicem 2 Automix [RUN], polymer-infiltrated ceramic (Vita Enamic [VE]) with Vita Adiva F-Cem [VAF] and acrylate polymer (CAD Temp [CT]) with RelyX Ultimate [RUL]. Fracture load and retentive force of the crowns were measured after 24 h water storage at 37 °C and after a chewing simulation followed by thermocyclic aging. Abrasion was recorded by matching stereolithography-data of the crowns obtained before and after chewing simulation. Additionally, the mechanical properties and bonding capabilities of the crown and cement materials were assessed. RESULTS Fracture load values were significantly highest for YZ > VE = CT. Retention force values did not differ significantly between the materials. The aging procedure did not affect the fracture load values nor the retention force significantly. Abrasion depth of the crowns was lowest for YZ followed by VE and CT. On unpolished crowns, abrasion of YZ and VE tended to be higher than on polished specimens. CONCLUSIONS Based on the obtained in-vitro results, all tested materials can be recommended for the use on zirconia implants, although CT is only approved for temporary crowns. The loading and retention capacity of the materials were not significantly affected by aging.

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ORIGINAL RESEARCH

Chewing simulation of zirconia implant supported restorations

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Chewing simulation of zirconia implant supported restorations

ABSTRACT

Purpose: To test three potential prosthetic material options for zirconia implants in regard to their mechanical properties, loading and retention capacity as well as to record abrasion after chewing simulation followed by thermocyclic aging.

Methods: Molar crowns (n=96) of three different CAD/CAM materials were produced and cemented on zirconia implants (ceramic.implant, Vita) with a diameter of 4.5mm. Monolithic zirconia (Vita YZ [YZ] with RelyX Unicem 2 Automix [RUN], polymer-infiltrated ceramic (Vita Enamic [VE]) with Vita Adiva F-Cem [VAF] and acrylate polymer (CAD Temp [CT]) with RelyX Ultimate [RUL]. Fracture load and retentive force of the crowns were measured after 24h water storage at 37°C and after a chewing simulation followed by thermocyclic aging. Abrasion was recorded by matching stereolithography-data of the crowns obtained before and after chewing simulation. Additionally, the mechanical properties and bonding capabilities of the crown and cement materials were assessed.

Results: Fracture load values were significantly highest for YZ>VE=CT. Retention force values did not differ significantly between the materials. The aging procedure did not affect the fracture load values nor the retention force significantly. Abrasion depth of the crowns was lowest for YZ followed by VE and CT. On unpolished crowns, abrasion of YZ and VE tended to be higher than on polished specimens.

Conclusions: Based on the obtained in-vitro results, all tested materials can be recommended for the use on zirconia implants, although CT is only approved for temporary crowns. The loading and retention capacity of the materials were not significantly affected by aging.

1 INTRODUCTION

Zirconia dental implants can be considered a promising alternative to the well-established titanium implants [1-6]. The elastic modulus of zirconia with 210 GPa [7] is however twice the one of titanium [8]. Therefore, the transmission of intraoral forces from the suprastructure to the implant and to the surrounding bone is different. As a consequence, for zirconia implants restored with veneered zirconia crowns in clinical studies, unacceptable rates of veneer chipping of up to 47% after up to 5 years have been reported [2,4,5,9], indicating stresses that were higher than the strength of the veneering ceramic itself or the bond strength between veneering ceramic and framework. It may be concluded that veneered zirconia is not suitable to restore zirconia implants.

To avoid the need of veneering, monolithic restorations might be considered. In laboratory studies, monolithic zirconia displayed a high fracture resistance irrespective of the cement applied [10,11]. This finding is supported for zirconia crowns on titanium [12], steel [13] and composite resin bases [14]. However, in this case the complete system composed of zirconia implant and zirconia restoration is rigid and the effect of stress distribution in the periimplant bone is unknown.

Another restorative approach for zirconia implants might be the use of a more elastic crown material to compensate for the high stiffness of the implant material. Compared to zirconia, lithium disilicate has a lower modulus of elasticity of 67 GPa [15]. For 22 monolithic crowns on zirconia implants a Kaplan-Meier success estimate of only 91,7% after 5 years was reported [16]. The incidence of significantly increasing occlusal roughness over time as reported may indicate an unfavorable stress distribution in the crown and questions the suitability of this material in a monolithic state for clinical application on zirconia implants in the premolar or molar region.

Further, laboratory results testing specific monolithic solutions for the prosthetic treatment of zirconia implants with more elastic materials such as polymer, composite or polymer-infiltrated ceramic are available [10,11,17]. The in-vitro fracture load of polymer-infiltrated ceramic on zirconia implants has been rated sufficient to withstand loads in the molar region if the restoration is fixed with an adhesive cement with a high compressive strength that is able to increase the loading capacity of the system [10,17].

Due to differences in test set-ups, the retrieved fracture load [10-14,17-20] or retention force [21,22] values can vary greatly for the respective materials. Parameters such as crown design, core material, preparation form, loading angle as well as cementation procedures influence the obtained values.

The effect of aging in the intraoral environment is simulated by subjecting the specimens to procedures such as dynamic loading and/or thermocyclic aging [12,18,19-21,23,24]. However, in most studies only fracture load or retentive force values of the whole system are measured and the components by themselves are not properly characterized, which leads to a lack of data to interpret the obtained results. The purpose of the present study was therefore to test three potential prosthetic treatment options for zirconia implants in regard to their mechanical properties, loading and retention capacity as well as to record abrasion after chewing simulation followed by thermocyclic aging.

2 MATERIALS AND METHODS

Three different restorative treatment options for a one-piece (monotype) zirconia implant were tested in regard to their loading and retention capacity as well as the respective materials mechanical and bonding properties and how they are affected by aging. The chosen materials were monolithic zirconia (Vita YZ T [YZ] with self-adhesive cement (RelyX Unicem 2 Automix [RUN]) for a simple handling, polymer-infiltrated ceramic (Vita Enamic [VE]) with an adhesive cement (Vita Adiva F-Cem [VAF]) with a high compressive strength [10] to sufficiently support the material and an acrylate polymer (CAD Temp [CT]) with an adhesive resin cement (RelyX Ultimate [RUL]) that is able to bond to the polymer via a universal primer [25] (Table 1). An overview of the tested parameters is given in Fig. 1.

2.1 Loading and retention capacity of the restorative system

Ninety-six zirconia implants (ceramic.implant, vitaclinical, Bad Säckingen, Germany) with a diameter of 4.5mm and a length of 10mm in the endosseous part were embedded with a 3mm clearance between implant neck and resin surface according to ISO 14801:2008 in epoxy (RenCast CW 20/Ren HY 49, Huntsman Advanced Materials, Duxford, UK).

One implant was scanned with an optical scanner (Omnicam, Sirona, Bensheim, Germany). A standardized molar crown (position 46) was designed by CAD-software (inLab SW3.88, Sirona) and milled (inLab MCXL, Sirona).

Thirty-two crowns of a zirconia (Vita YZ T, Vita Zahnfabrik, Bad Säckingen), 32 crowns of a polymer-infiltrated ceramic (Vita Enamic, Vita) and 32 crowns of an acrylate polymer (Vita CAD-Temp, Vita) were produced following the manufacturer's recommendations. The occlusal surfaces of 16 crowns from each material for the fracture load test were polished with ceramic polishers and finalized by goat hair buffing wheel and polishing paste (Wetzler Dental, Bielefeld, Germany). Polished and unpolished crowns were used to evaluate the effect of the surface finish on abrasion. All crowns were cemented on the zirconia implants according to the pretreatments provided in Table 2 for the respective material combination according to the manufacturers recommendations. The crowns were filled with cement, placed on the implants and loaded with 25N for 10min at room temperature using a custom-made device. Light-curing was applied afterwards for 60s per crown (20s from occlusal, buccal and oral site) (Elipar DeepCure-S, 3M Espe, Neuss, Germany). The specimens were then stored in 37°C distilled water for 24h (CTS T-4025, Hechingen, Germany).

Eight of the polished specimens of each material were then subjected to a fracture load test using a universal testing machine (Zwick Z020, Zwick/Roell, Ulm, Germany). A steel ball (4.5mm diameter) was adjusted in the center of the occlusal surface with a 0.2mm thick tin foil (Dentaurum, Pforzheim, Germany) placed between the ball and the occlusal surface to attain a homogenous stress distribution. Fracture load testing was performed at a cross-head speed of 1mm/min and the fracture load values were recorded (testXpert V 2.2, Zwick/Roell).

Eight of the unpolished specimens of each material were subjected to a crown retention test. The crowns were removed at a crosshead speed of 1mm/min (Zwick Z020, Zwick/Roell) in a custom specimen holder from the implants parallel to the implant axis and retention force was recorded (textXpert v2.2; Zwick/Roell).

The other 16 specimens of each material were subjected to aging followed by either the fracture load test of the 8 polished specimens or retention test of the 8 unpolished specimens as described above. For the aging simulation, the crowns were first placed in a chewing simulator (CS-4.8, SD Mechatronik, Feldkirchen, Germany) and subjected to 1.2 Mio cycles [20,23,24,26,27] with a frequency of 1.5Hz (maximal capacity of the chewing simulator) and a force of 49N to initiate subcritical crack growth [20,26-28]. Steel balls with a diameter of 4.5mm served as antagonists. The specimen chambers were filled with 37°C water. Afterwards, the specimens were subjected to 20'000 thermal cycles of 5 and 55°C with a dwell time of 30s (THE-1100, Mechatronik). Fracture origins and abrasion of unpolished specimens were visualized after mechanical testing using light (Wild M7A, Leica, Heerbrugg, Switzerland) and scanning electron microscopy (Philips XL30 FEG ESEM, Philips Electron Optics, Eindhoven, the Netherlands).

2.2 Abrasion

The occlusal surface of each crown was scanned before and after aging (Cerec Omnicam, Sirona, Bensheim, Germany). Stereolithography (STL) data was exported and matched using the OraCheck software (V2.10.6044, Cyfex, Zurich, Switzerland). The diameter of the implant served as reference for the software calibration. The abrasion volumes as well as maximum abrasion depth (mean of maximum 10% deviations) for each specimen were calculated.

2.3 Mechanical properties of restorative materials

Mechanical properties as stated below were measured for the restorative materials YZ, VE and CT after 24h water storage at 37°C (baseline) as well as after aging, meaning storage in water of 37°C for 24h, followed by 20'000 thermal cycles (THE-1100, SD Mechatronik).

2.3.1 Flexural strength

Flexural strength of the restorative materials YZ, VE and CT was measured using the 3-point bending test. Bending bars of YZ and VE with a dimension of 1.2x4.0x20.0mm (ISO 6872: 2015) and of CT with a dimension of 2.0x2.0x25.0mm (ISO 4049: 2018) were produced out of CAD/CAM blocs (n=10 per group). Specimens of VE and CT were manually grinded with silica paper (P1200) to the final dimensions. YZ specimens were cut over dimensioned, grinded (D91; FSM 480 A, Knuth, Wasbek, Germany) and sintered according to the manufacturers' recommendations (Zyrcomat, Vita). Edges of the ceramic specimens were chamfered according to ISO 6872. Three-point bending test was performed at a crosshead speed of 0.5mm/min until fracture (Z020, Zwick/Roell). The roller span for YZ and VE was 12mm, for CT 20mm. Flexural strength σ was calculated using the following formula:

$\sigma = 3Fl/2wh^2$

F is the fracture load; l is the roller span; w is the width and h is the height of the bar.

2.3.2 Fracture toughness

Fracture toughness was measured according to ISO 24370:2005. Five bending bars per group with a dimension of 4.0x3.0x45.0mm were produced as described above. Cutting of the notch followed the recommendations of the standard. Depth of the notch was recorded with light microscopy for each specimen separately after the test to vary between 0.72 and 0.88mm (i.e. 0.8±0.08mm). Specimens were loaded until fracture (Z010, Zwick/Roell) at a crosshead speed of 0.5mm/min. Fracture toughness K_{IC} was calculated according to ISO 24370:2005 using the following formula:

$K_{IC} = Y^*_{min} [F(S_0 - S_i)/BW^{3/2}]$

$Y^*_{min} = (3.08 + 5.00\alpha_0 + 8.33\ \alpha_0^2)[1+0.007(S_iS_0/W^2)^{½}][(\alpha_1 - \alpha_0)/(1 - \alpha_0)]$

F is the fracture load; S_0 is the outer span; S_i is the inner span; B is the test specimen thickness; W is the test specimen width; Y^*_{min} is the stress intensity factor coefficient; α_0 is a_0/W; α_1 is a_1/W; a_0 is the chevron tip dimension; a_1 is the mean chevron dimension.

2.3.4 Hardness

Vickers and Martens hardness were determined on flexural strength specimens of all materials with a universal testing machine (ZHU 2.5, Zwick/Roell, Ulm, Germany), using a Vickers indenter. A load of 9.8N with a dwell time of 15s was applied.

2.4 Compressive strength of cement materials

Compressive strength was measured for the cement materials RUN, VAF and RUL after 24h water storage at 37°C (baseline) as well as after subjecting the specimens to an aging procedure with water storage at 37°C for 24h followed by 20'000 thermal cycles (THE-1100, Mechatronik). Cylindrical test specimens 3mm in height and diameter of RUN, VAF and RUL (n=10 per group) were produced as described for the indirect tensile strength test. Specimens were loaded axially until fracture at a cross-head speed of 1mm/min (Z020, Zwick/Roell) and compressive strength was calculated using the following formula:

$\sigma_c = F/\pi(d/2)^2$

F is the fracture load; d the specimen diameter and h the specimen height

2.5 Bonding properties

Shear bond strength was measured between the restorative materials and the cements (YZ/RUN, VE/VAF, CT/RUL) as well as between the implant material and the cements (Impl/RUN, Impl/VAF, Impl/RUL) at baseline (24h water storage at 37°C) and after aging (24h water storage 37°C, 20'000 thermo cycles). Twelve substrates per group were cut to a dimension of 14x12x3mm and pre-treated as it was done for the cementation of the crowns (Table 2). The zirconia substrate of the implant was provided by the manufacturer in the required dimension and with a surface similar to the abutment surface. An acrylic cylinder (D+R Tec, Birmensdorf, Switzerland) with an inner diameter of 2.9mm was fastened vertically on the pretreated substrate, cement was applied through the opening of the cylinder, compressed with a headless steel screw with a force of 1N and light-cured for 60s (Elipar DeepCure S, 3M Espe). Shear bond strength test was performed at a crosshead speed of 1mm/min using a universal testing machine (Z020, Zwick/Roell).

2.6 Statistics

Data was tested for normal distribution. Logarithmic transformation was applied for data of shear bond strength test due to the variations in standard deviations. Statistical analysis was performed using two-way ANOVA to check for the effect of the applied material and aging protocol ($p<0.05$). For the abrasion data the effect of the material and surface finish was tested. Post-hoc test Fisher LSD was applied afterwards to determine differences within the subgroups.

3 RESULTS

No damage besides the abrasion was detected on all crowns after the aging procedures. Mean and standard deviations of the loading and retention capacity of the restorative system before and after aging are displayed in Fig. 2. For the fracture load, two-way ANOVA revealed a significant effect of the material applied ($p<0.001$) but no effect of the aging protocol ($p=0.311$). Within the factor material post-hoc Fisher LSD test displayed that fracture load values of YZ were significantly higher than those of VE and CT ($p<0.001$). While performing the fracture load test of YZ, three of the implants in each group, baseline and aging, fractured through the upper endosseous part at a mean force of 3003±1212N. The values of the fractured implants were not included into Fig. 2 and the statistical analysis for YZ crowns. At maximum load, the crowns of all materials fractured into 2-6 pieces. Fracture was observed by light and scanning electron microscope to mainly initiate from the occlusal loading point (Fig. 3). For VE and CT, the cement remained on the restorative material fragments after fracture. For YZ crowns the cement was sticking to both, implant and crown.

For the retention force no effect of either material ($p=0.168$) or aging protocol ($p=0.649$) was observed (Fig. 2). No visible damage was detected on the crowns of YZ and CT from the retention test. On 4 VE crowns within each group, minor chipping fractures <2mm were observed at the cervical part of the crowns. The cement used for VE/VAF and CT/RUL remained inside the crown after removal. The cement RUN that was applied for YZ broke; the upper half remained inside the crown while the cervical part up to the middle of the abutment remained on the implant, but was easy to remove.

A randomly selected example for the observed abrasion on each material by matching STL-data from before and after aging (chewing simulation and thermal cycling) is displayed in Fig. 4.

The abrasion volumes and the abrasion depths are displayed in Table 3. For the interpretation of the abrasion volume it has to be considered that for YZ and especially for VE not only abrasions but also build-ups around the abrasion were observed that were automatically subtracted from the abrasion volume. Therefore, the abrasion depth was additionally evaluated. The abrasion depth was significantly affected by the material ($p<0.001$) and was significantly highest for CT>VE>YZ. For unpolished specimens of VE and YZ, abrasion tended to be higher than for polished specimens. The means of the abrasive volume correlated linearly to the abrasion depth ($y=0.001x$, $R^2=0.984$).

The results for the mechanical properties of restorative and cement materials as well as the bonding properties are presented with the statistics in Table 4.

4 DISCUSSION

In the present study three potential prosthetic treatment options for zirconia implants were tested in regard to their mechanical properties, loading and retention capacity as well as abrasion after chewing simulation followed by thermocyclic aging.

The obtained fracture load values for all tested material combinations were higher than the maximum chewing forces in the molar region that are reported to vary between 600N and 1200N [29,30]. Physiological chewing forces are however lower and range within 110N to 125N in the molar region [31]. Fracture loads were of course highest for YZ due to the materials' high flexural strength and fracture toughness. For three specimens of each YZ group, the loading capacity of the YZ crowns was even higher than the one of the zirconia implants and consequently, the implants fractured. The implants fractured at forces that were almost three times higher than the maximum chewing forces. Hence, the risk of an implant fracture in clinical use is low. However, the results indicate that the implant might be the weakest link when restored with a zirconia restoration.

The loading capacities of VE and CT were statistically similar, although the fracture load of CT was slightly but not statistically significant decreased after aging whereas VE remained stable. CT may be more sensitive to aging due to its higher polymeric content that absorbs water over time [32], which is probably also the cause of the decrease in flexural strength of CT after thermocyclic aging. However, as water absorption is a surface effect, no significant impact on the loading capacity of the CT crowns was observed. That might be explained by the higher volume-to-surface ratio of the crowns compared to the flexural strength specimens. VE also revealed a decrease in flexural strength after thermal cycling, probably due to the polymeric portion as well. However, the fracture load of VE was not affected by thermal cycling. The cement VAF that was applied for VE revealed a significantly higher compressive strength than RUL that was used for CT. For VE it is known that a high compressive strength of the resin composite cement can improve the fracture load values [10,17]. Thus, the higher compressive strength of VAF might have compensated the decrease in flexural strength of VE. Previous fracture load values [10] that were reported after 24h water storage at 37°C for VE with VAF (1297±150N) on zirconia implants were lower than those obtained in the present study (1592±271N). The implant diameter of the zirconia implant in the previous study was 4.0mm, in the present 4.5mm while the outer crown contour and test set-up was the same. The increased diameter of the abutment must have resulted in a better distribution of the loading force within the crown material. Further, the crowns in the present study were treated with primer and the cement was light-cured while the VE crowns of the previous study were cemented without primer and the cement was cured by autopolymerization [17]. Fractures of all-ceramic restorations in clinical use occur at considerably lower forces than observed in the present investigation [33]. It has to be acknowledged that crowns on one-piece zirconia implants display an increased wall thickness due to the small geometry of the abutment part. Thus, the load bearing capacity of these restorations is higher than that of ceramic restorations placed on individually designed abutments as applied for some restorations on titanium implants.

The fractures of the present study mainly initiated from the loading point due to the high force that was applied. Crown fractures in clinical situations may be caused by critical stress concentrations, cyclic fatigue (subcritical crack growth) or occur as a result of processing flaws or inadequate restoration design [34]. Consequently, crack initiation and crack propagation are more complex and usually induced by multiple fracture origins [35]. Features like compression curl, hackle, wake hackle, twist hackle, and arrest lines are commonly found markings in failed ceramic restorations [36-39]. For zirconia crowns on implants it has been observed that especially restorations with thin walls in the cervical region connecting the crown to the implant are vulnerable to contact damage [35].

The retention capacity of all crown materials that were fixed on the zirconia implants with resin composite cements were similar and not affected by the aging process. Concerns have been raised regarding the long-term bonding capability to zirconia [40] and polymer [41]. The results obtained in the present study indicate clearly that although shear bond strength values to both crown and implant varied significantly among the materials, they did not seem to substantially affect the crown retention. That the retention capacity of the crowns was neither affected by the material used nor the aging process must therefore be mainly due to the high strength and stability of the applied resin composite cements rather than their bonding capability. It has been proposed that a tight fit of the cement layer on the implant abutment and the intaglio surface of the crown results in a vacuum effect that has to be overcome in order to remove the crown [22]. In the literature, the retention capacity of only VE [22] and lithium disilicate [21] crowns on zirconia abutments has been evaluated using different cements. Lithium disilicate crowns cemented with RUN displayed a significant decrease in retention force after thermal cycling [21], which is in contrast to the present results where retention force of YZ crowns cemented with RUN was not affected by thermal cycling. It might be that a different fit of the crowns, and the resulting cement thickness influences the outcome. No significant difference has been reported regarding the retention capacity for VE crowns cemented with either one of the resin composite cements VAF, RUN or RUL irrespective if primer was applied or not [22].

The chewing simulation of 1.2 Mio cycles that was applied with a force of 49N is reported to simulate aging in the mouth of 5 years [18,42]. In most studies where a chewing simulation is applied, steatite is used as an antagonist [20,24,26-28,42]. Steel was chosen in the present study to potentially increase the aging effect and simulate a worst-case situation. Despite the intensified stress the loading and retention capacity of the tested materials were not affected significantly by the aging procedure. Therefore, for future studies fracture load and retention values after 24h are recommended by the authors to test basic material behavior. In addition, thermocyclic aging of the components may be further performed to estimate their aging potential. The specimens used for testing the mechanical properties of the materials reveal a more delicate shape with a higher surface/volume ratio than when they are tested as a crown-cement-implant system and are therefore more susceptible to aging protocols.

Chewing simulation of crowns can be used to visualize the abrasion potential of different materials, however, ball-on-disc wear simulations seem more adequate to estimate a materials' wear potential [15,43,44] due to the increased control of the load application on the substrates topography. Additionally, ball-on disc wear simulations consider lateral load movements as they occur during chewing, thus evaluate abrasion more precisely than the performed chewing simulation. In the present study the aim was to include the effect of the topography of the occlusal surface and the differences in the complex elastic behavior of the whole system comprising implant, cement, and crown. Abrasion was higher for CT than for VE and YZ. Although there has been a tendency towards an increased abrasion for materials with low hardness values as also observed in the present study, the abrasion potential of a material does not correlate directly to their hardness [15,43]. The occlusal surface finish is important, especially for materials with ceramic content because abrasion tended to be higher for unpolished specimens of VE and YZ than for the polished ones. In a previous study the wear of enamel antagonists to machined, polished or glazed zirconia was analyzed. Glazed zirconia surfaces resulted in a significantly higher abrasion of the enamel antagonist than machined zirconia, which was also significantly higher than polished surfaces [44]. For VE, abrasion after chewing simulation has been previously analyzed using a microCT with similar results as in the present study [28]. Abrasion of VE is similar as for human enamel [43]. Material build-up around the abrasion as it was found for YZ and VE was due to wear of the steel antagonist for YZ and for VE the material itself was found to be pushed to the rim of the abrasion area.

All tested material combinations in the present study have their advantages and disadvantages but seem all suitable for the restorative single crown treatment of zirconia implants in the molar region. Monolithic zirconia should be the material of choice in situations when esthetic demands are not in focus and easy handling of the cementation process is required. However, it has to be acknowledged that if overload occurs it is likely to affect the implant instead of the zirconia crown. Considering this aspect, the elastic crown materials with their lower strength may be more suitable. Polymer-infiltrated ceramic with an adhesive cement with high compressive strength is the material for any situation where an adequate cementation can be performed. Another option would be the use of polymer crowns with a cement providing the proper universal adhesive for a polymeric bond. However, no data is available on the long-term performance of CT crowns because the material is currently only approved for a temporary crown solution by the manufacturer.

The outcomes of a clinical study based on the present results, which is currently performed at the University of Zurich, will provide more information on a proper materials choice for the restorative treatment of zirconia implants.

5 CONCLUSION

Within the limitations of this study it can be concluded that:

- All tested materials can be recommended for the use on zirconia implants, however polymer crowns are currently only approved for a temporary crown solution by the manufacturer.

- The loading and retention capacity of the tested materials are not affected significantly by aging with a chewing simulation.

- No correlation was observed between mechanical properties and loading or retention capacity of the respective materials.

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TABLES AND FIGURES

TABLE 1 - Restorative and cement materials used.

TABLE 2 - Pretreatment of the respective materials.

TABLE 3 - Means and standard deviations of the abrasion volume (V) and the abrasion depth (d) at the occlusal surface of the either polished or unpolished crowns of YZ, VE and CT.

TABLE 4 - Means and standard deviations of the mechanical properties of restorative and cement materials and bonding properties between restorative materials and cements as well as between implant and cements. Statistical similar groups obtained with the post-hoc test are marked with superscript letters within one property group, for vertical comparison uppercase, horizontal comparison lower case letters.

FIG. 1 - Testing diagram for the restorative treatment options on the zirconia implant and table of the parameters that were tested separately for the respective materials.

FIG. 2 - Loading capacity and crown retention means and standard deviation after 1d water storage at 37°C (Baseline) and after chewing simulation followed by thermocyclic aging (Aging).

FIG. 3 - Light microscopic images of gold-coated fractured crowns of YZ, VE and CT. Arrows indicate fracture paths.

FIG. 4 - Abrasion images of unpolished crowns of YZ, VE and CT after aging in the chewing simulator given by matching STL data with the software Oracheck.

Material	Type	Name	Code	Lot-Nr.	Manufacturer
Restorative	Zirconia	Vita YZ T	YZ	57161	Vita Zahnfabrik Bad Säckingen Germany
	Polymer-infiltrated ceramic	Vita Enamic	VE	45360	
	Acrylate polymer	Vita CAD-Temp	CT	28440	
Cement	Self-adhesive resin composite	RelyX Unicem 2 Automix	RUN	607206	3M Espe Seefeld Germany
	Adhesive resin composite	Vita Adiva F-Cem	VAF	71702177	Vita Zahnfabrik Bad Säckingen Germany
		RelyX Ultimate	RUL	657610	3M Espe Seefeld Germany

TABLE 1 - Restorative and cement materials used.

Restorative material	**Zirconia (YZ)**	**Polymer-infiltrated ceramic (VE)**	**Acrylate polymer (CT)**
Pretreatment Crown	Sandblasting Al_2O_3 50µm with 2bar	Ultrasonic cleaning with 70% ethanol for 4min	Sandblasting Al_2O_3 50µm with 2bar
	Ultrasonic cleaning with 70% ethanol for 4min	HF 5% etching for 60s	Ultrasonic cleaning with 70% ethanol for 4min
	-	Silane (Vitasil) for 60s	Primer (Scotchbond Universal Adhesive) for 20s
Cement	**Self-adhesive resin composite (RUN)**	**Adhesive resin composite (VAF)**	**Adhesive resin composite (RUL)**
Pretreatment Abutment	Ultrasonic cleaning with 70% ethanol for 4min		
	-	Primer (Vita Adiva ZR-Prime) for 10s	Primer (Scotchbond Universal Adhesive) for 20s
Implant abutment	**Zirconia (ceramic.implant)**		

TABLE 2 - Pretreatment of the respective materials.

	YZ		VE		CT	
	polished	unpolished	polished	unpolished	polished	unpolished
V (mm^3)	0.01±0.01	0.02±0.03	0.02±0.05	0.07±0.07	0.14±0.09	0.13±0.11
d (μm)	11.2±2.1	28.6±18.2	33.7±17.6	64.6±33.8	128.5±34.7	130.7±48.2

TABLE 3 - Means and standard deviation of the abrasion volume (V) and the abrasion depth (d) at the occlusal surface of the either polished or unpolished crowns of YZ, VE and CT.

	Baseline 24h water storage 37°C	Aging 24h water storage 37°C + 20'000 thermal cycles
Restorative materials		
Flexural strength (MPa)		
YZ	988.5±115.3^{A,a}	978.3±93.1^{A,a}
VE	132.7±17.0^{B,a}	114.2±6.3^{B,b}
CT	100.4±3.6^{C,a}	88.7±3.9^{C,b}
Fracture toughness (MPa√m)		
YZ	6.20±1.22^{A,a}	5.11±0.49^{A,b}
VE	1.82±0.29^{B,a}	1.19±0.02^{B,b}
CT	1.72±0.28^{C,a}	1.05±0.02^{C,a}
Vickers Hardness (HV1)		
YZ	1553.3±88.5^{A,a}	1625.7±23.0^{A,b}
VE	151.9±2.4^{B,a}	272.8±21.5^{B,b}
CT	30.3±1.1^{C,a}	33.7±2.6^{C,a}
Martens Hardness (N/mm^2)		
YZ	7537.4±604.3^{A,a}	5713.2±818.0^{A,b}
VE	1019.2±113.8^{B,a}	1059.0±230.7^{B,a}
CT	151.1±7.7^{C,a}	165.8±8.6^{C,a}
Cement materials		
Compressive strength (MPa)		
RUN	283.2±17.3^{A,a}	273.1±28.2^{A,a}
VAF	385.4±22.5^{B,a}	389.8±15.1^{B,a}
RUL	293.5±10.5^{A,a}	286.6±14.5^{A,a}
Bonding properties		
Shear bond strength (MPa)		
YZ/RUN	3.3±3.7^{A,a}	2.4±4.0^{A,a}
VE/VAF	9.9±0.6^{B,a}	10.0±1.2^{B,a}
CT/RUL	22.8±2.0^{C,a}	20.4±2.4^{C,a}
Shear bond strength (MPa)		
Impl/RUN	0.0±0.0^{A,a}	0.0±0.0^{A,a}
Impl/VAF	3.8±0.9^{B,a}	0.0±0.0^{A,b}
Impl/RUL	13.2±2.9^{C,a}	8.8±1.4^{B,b}

TABLE 4 - Means and standard deviations of the mechanical properties of restorative and cement materials and bonding properties between restorative materials and cements as well as between implant and cements. Statistical similar groups obtained with the post-hoc test are marked with superscript letters within one property group, for vertical comparison uppercase, horizontal comparison lower case letters.

FIG. 1 - Testing diagram for the restorative treatment options on the zirconia implant and table of the parameters that were tested separately for the respective materials.

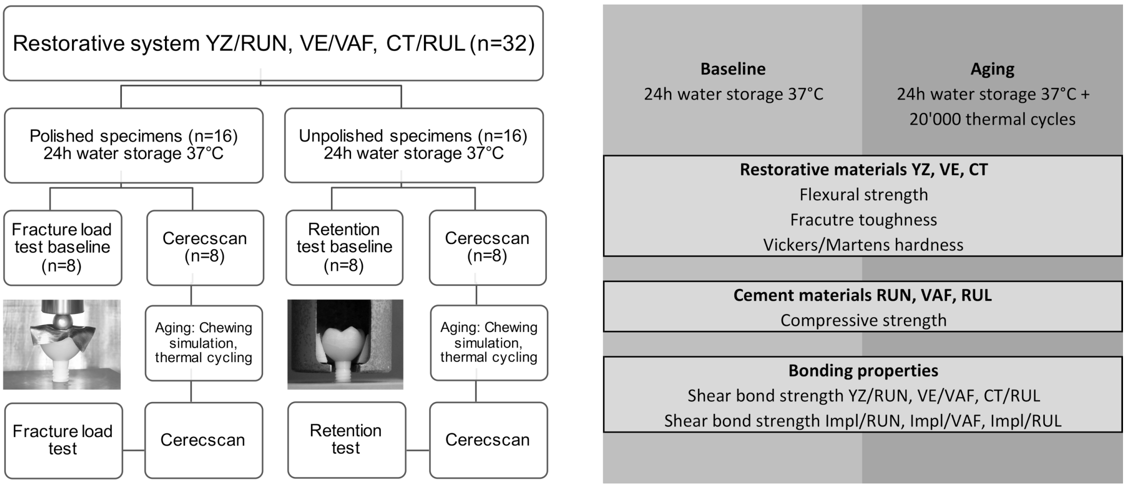

FIG. 2 - Loading capacity and crown retention means and standard deviation after 1d water storage at 37°C (Baseline) and after chewing simulation followed by thermocyclic aging (Aging).

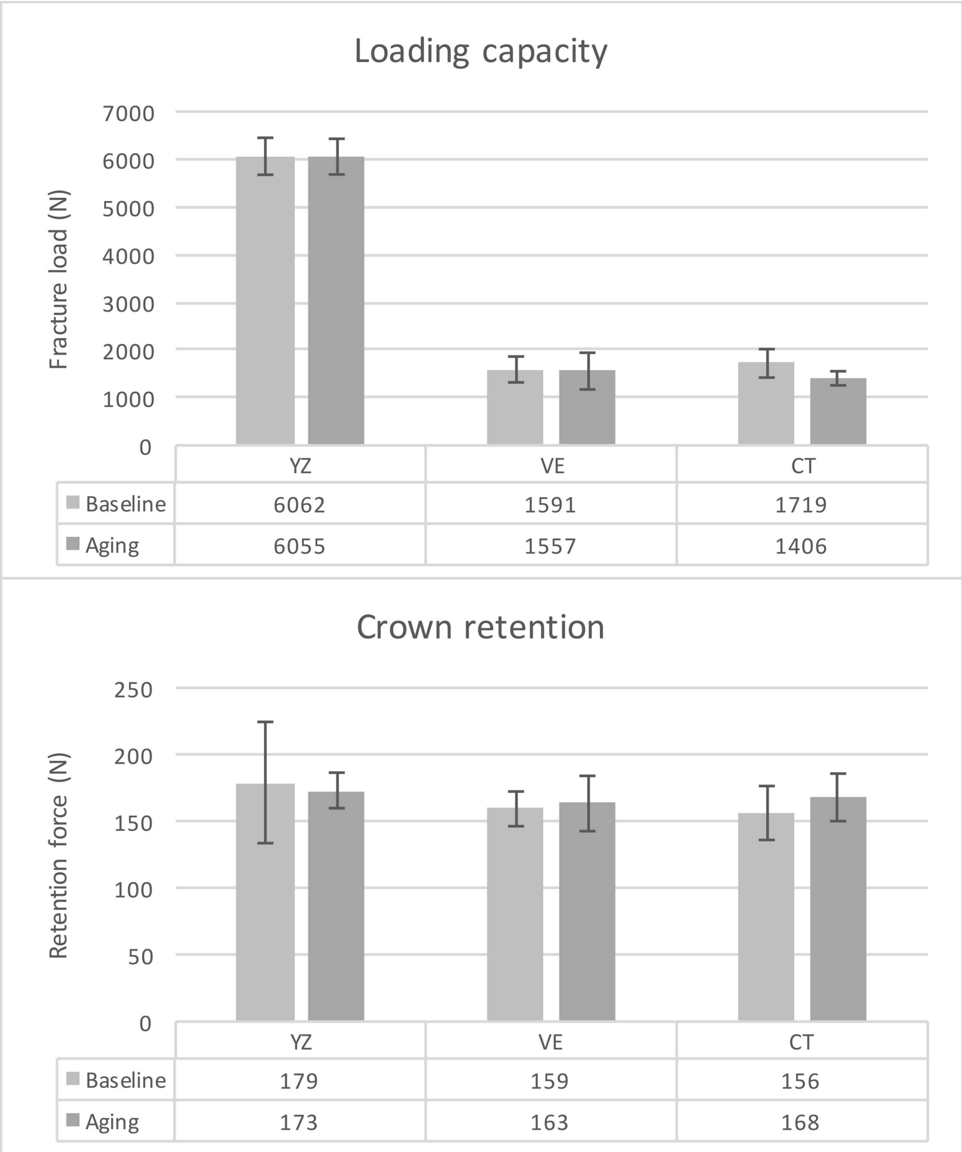

FIG. 3 - Light microscopic images of gold-coated fractured crowns of YZ, VE and CT. Arrows indicate fracture paths.

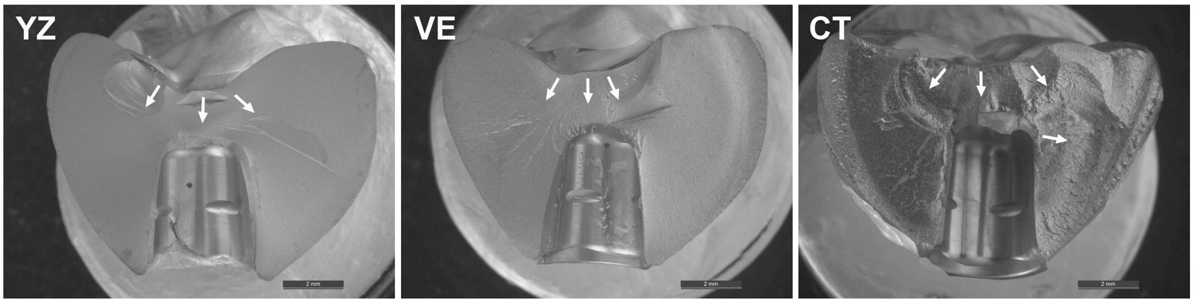

FIG. 4 - Abrasion images of unpolished crowns of YZ, VE and CT after aging in the chewing simulator given by matching STL data with the software Oracheck.